

Influences of Asymmetric Flow Features on Hurricane Evolution

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LONG-TERM GOALS

It is now recognized that asymmetric processes have a significant impact on the evolution of a symmetric hurricane vortex; the factors that determine the degree to which these processes create changes in hurricane structure and intensity are nevertheless not well understood. Our diagnosis will isolate these factors, especially those leading to rapid deepening.

OBJECTIVES

The broad objective of this research is to investigate the influence of ambient asymmetric flow features, including those associated with upper-level troughs, on the structure and intensification of hurricanes.

The specific objectives of the current effort are:

1. To continue our diagnosis of hurricane structure and intensity change as predicted by the Geophysical Fluid Dynamics Laboratory (GFDL) model using the technique of potential vorticity inversion;
2. To continue our study with the full-physics NCAR/Pennsylvania State MM5 numerical model to evaluate the impact of cumulus convection asymmetries on the intensification of a hurricane vortex.

APPROACH

The approach of our continuing diagnostic analysis involves the use of potential vorticity (PV) to evaluate and understand the impact of ambient environmental flow features on the structure and intensification of hurricanes in real-data numerical forecasts of the Geophysical Fluid Dynamics Laboratory (GFDL). PV is the natural context in which to understand three-dimensional hurricane dynamics. A particularly powerful application of PV analysis is that of piecewise PV inversion, which allows the evaluation of the wind and temperature fields associated with a given atmospheric feature, such as an upper-level trough. The study of Shapiro and Möller (2003) was the first to use the method of piecewise PV inversion to diagnose the asymmetric features that contribute to tropical cyclone intensification. The hurricane in question was Hurricane Opal of 1995, which developed rapidly over the Gulf of Mexico before weakening as it approached the Gulf coast. During its intensification phase the hurricane interacted with an approaching upper-level trough. Although it was one of the most

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intensely studied hurricanes ever, the cause of Opal's intensification is still a matter of controversy. The results of Shapiro and Möller (2003) gave no indication that the upper-level trough was a significant contributor to Opal's lower-tropospheric intensification. Our continuing research diagnoses GFDL model forecasts for other hurricanes in order to determine if the results for Opal were an anomaly or the rule. Diagnoses of analyses derived from a real data case are also being made.

The approach of our continuing study with the MM5 model involves the diagnosis of idealized numerical experiments to evaluate the impact of asymmetric cumulus convection on the intensification of a hurricane vortex. Diabatic heating associated with deep cumulus convection creates PV anomalies. Fundamental studies with dry dynamics (no cumulus convection) have diagnosed the impact of PV asymmetries on an idealized symmetric tropical cyclone vortex (Möller and Montgomery 1999, 2000). Shapiro (2000) used a simple three-layer numerical model including a convergence-based convective parameterization scheme to understand the role of cumulus convection and the atmospheric boundary layer in the interactions between asymmetric PV anomalies and a hurricane vortex. This study showed that convection plays an important role in determining how a hurricane responds to the anomalies in its environment. Our research uses the NCAR/Pennsylvania State full-physics nonhydrostatic multi-level numerical model (MM5) to evaluate the influence of asymmetric features on the evolution of a hurricane vortex in a more realistic setting than in Shapiro (2000). Rather than adding winds and temperatures in balance with a specified PV asymmetry, as in Moeller and Montgomery (1999, 2000) and Shapiro (2000), a diabatic heating asymmetry is imposed on a spun-up hurricane vortex instead.

In the continuing diagnosis of the GFDL model forecasts and the real-data analyses as well as the study of idealized numerical experiments with the MM5 model, the PI, Dr. Lloyd Shapiro, works in close collaboration with Dr. Dominique Möller, who is also supported with the ONR grant.

WORK COMPLETED

Preliminary results of diagnoses of GFDL model forecasts for Hurricane Bertha of 1996 and Hurricane Erin of 2001 were reported in Shapiro and Möller (2004). The paper Shapiro and Möller (2005), presenting the results of the analysis, was accepted for formal publication. The conclusions of the study are briefly described in the following section. Diagnoses of Hurricane Gloria of 1985, based on analyses obtained from the Hurricane Research Division/NOAA, have begun. The piecewise PV inversion applied in the diagnostic analysis of GFDL and real data uses the asymmetric balance (AB) formulation of Shapiro and Montgomery (1993). A study has been completed that evaluates the accuracy of the AB formulation using a simple numerical model. A paper, Sölch et al. (2005), that reports the results of the study (very briefly summarized in the next section) has been submitted for publication.

The paper Möller and Shapiro (2005) on the influences of asymmetric heating on hurricane evolution in the MM5 model was accepted for formal publication. Preliminary results were reported in Möller and Shapiro (2004). The following section contains a brief description of the study's conclusions.

RESULTS

The completed diagnosis of GFDL model forecasts of Hurricane Bertha of 1996 and Hurricane Erin of 2001 contrasts the influence of ambient upper-level atmospheric troughs on their intensification. Both hurricanes intensified rapidly as they approached the east coast of the United States. Both hurricanes

had upper-level troughs in their vicinity that could have affected their evolution. The piecewise PV inversion technique allows a quantitative diagnosis of the impact of the respective troughs on the hurricane's intensification. The piece of PV selected for the diagnosis of Hurricane Bertha was restricted to upper levels and outer radii, including a nearby upper-level trough to the north. At the time of the analysis, during a period of rapid deepening, the surface inner-core symmetric tangential wind tendency associated with this piece of PV was an acceleration on the order of 25 m/sec/day. This intensification rate is comparable to the observed and model-simulated intensification rate. By contrast, for Hurricane Erin the surface inner-core symmetric tangential wind tendency associated with a similar piece of PV, including an upper-level trough to the east as well as one to the west, was a deceleration on the order of -10 m/sec/day. The evidence is thus that the upper-level troughs did not directly enhance Erin's rapid intensification at the time of the analysis. An additional piecewise PV diagnosis of the wind at the center of the hurricane indicates that upper-level relative flow toward the northeast due to the upper-level troughs could have indirectly contributed to Erin's intensification. The piecewise inversion technique has thus proven to be a powerful tool in distinguishing between cases where upper-level troughs clearly favor hurricane intensification (Hurricane Bertha) and those where they do not (Hurricane Opal and Erin). The completed study of the accuracy of the AB formulation compares this system with the standard balance equations (BE). Linearized equations for the evolution of disturbances on a symmetric hurricane-like vortex are used to compare forecasts using the BE and AB formulations with benchmark primitive equation shallow-water model forecasts. In forecasts where the Froude number (which measures the potential strength of divergence relative to vorticity) is not large and the divergence of the asymmetric disturbances is in fact large, which is the case in the inner region of a mature hurricane, the AB system (which allows for large divergence) proves to be a useful alternative to the BE formulation, especially for disturbances with small azimuthal wavenumbers (Fig. 1).

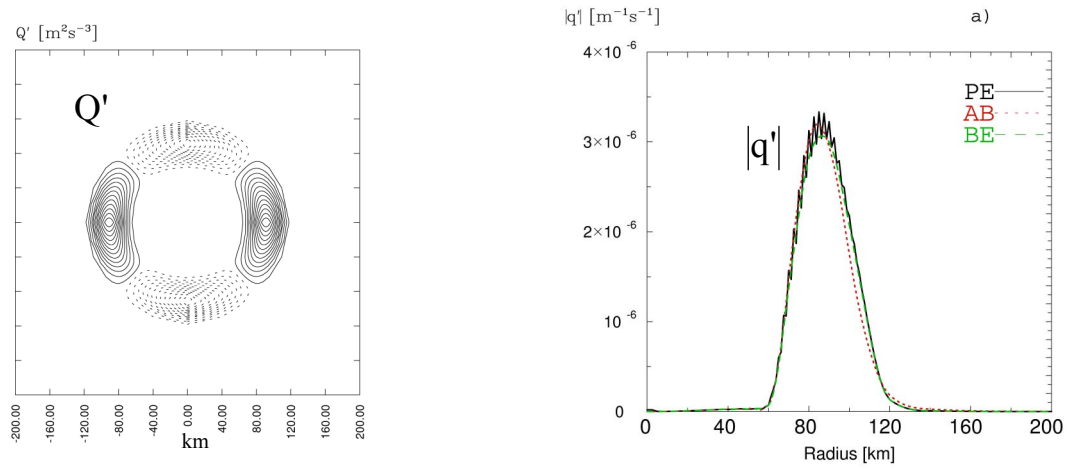


Figure 1. Amplitude of asymmetric potential vorticity (azimuthal wavenumber $n=2$) after 12 h for AB, BE and benchmark primitive equation (PE) shallow-water experiments (right panel: magnitude of asymmetric PV, $|q'|$ as a function of radius) with $n=2$ mass source (left panel: horizontal distribution of mass source, Q') on a deep symmetric hurricane-like vortex, indicating comparable accuracies of the AB and BE balance formulations.

The piecewise PV inversion technique is being applied to a real data case from a synoptic analysis of Hurricane Gloria of 1985. This analysis, made by the Hurricane Research Division (AOML, NOAA), combines inner-core Doppler, synoptic-scale dropwindsonde and global analyses over a large domain. Preliminary analyses indicate that asymmetric features in the hurricane's environment tended to spin down its inner-core region. Work is underway to reconcile tangential wind tendencies derived from observed asymmetric winds and heights from those derived from balanced quantities. Since inner-core thermodynamic data are not available, a new "balance equation" to derive the height field from the wind using the AB theory is being developed.

The completed study on the influences of asymmetric heating on hurricane evolution in the MM5 establishes the importance of the structure of a hurricane in determining the impact of cumulus convection asymmetries on the hurricane's intensification. The full-physics nonhydrostatic mesoscale model MM5 is used to evaluate the influence of convectively-generated asymmetries on a symmetric hurricane vortex. Rather than adding winds and temperatures in balance with a specified PV asymmetry, or temperature perturbations themselves, to a symmetric vortex as in previous studies, a diabatic heating asymmetry is imposed on a spun-up model hurricane. The diabatic heating creates wind and temperature asymmetries that interact with the model hurricane vortex. The impact of short (1 h)-duration monochromatic azimuthal-wavenumber diabatic heating on the short- and long-term evolution of the azimuthally-averaged vortex is evaluated, and an angular momentum budget is made to determine the mechanisms responsible for the short-term impact. It is found that the small eddy kick created by the additional diabatic heating asymmetry leads to a substantially-amplified long-term change in the vortex, with episodes of strong relative weakening and strengthening $\sim 5\text{-}10$ m/sec following at irregular intervals. This behavior is diabatically controlled. It is found that the symmetric secondary circulation is active in creating the short-term changes in the azimuthally-averaged vortex, and is not simply a passive response as in previous studies with dry physics. A central conclusion of the study is that the structure of the spun-up hurricane vortex, in particular pre-existing asymmetric features, controls the character of the response to the additional diabatic heating asymmetry. Since in practice hurricanes are not symmetric, the study places the insights gained from previous fundamental studies of the influence of asymmetries on strictly symmetric vortices in perspective. The results also imply that a small change in the factors that control convective activity will have a substantial lasting consequence for the intensification of a hurricane.

IMPACT/APPLICATIONS

The results of the diagnostic studies with the GFDL numerical hurricane forecast model are being used to isolate the physical mechanisms by which some atmospheric upper-level troughs appear to weaken a hurricane while others appear to intensify one. The results will help to elucidate reasons for good and bad forecasts from the GFDL model, and thereby aid in improvement of this and other numerical hurricane forecast models.

The results of the idealized numerical experiments to study the impact of asymmetric cumulus convection on the intensity of a symmetric hurricane vortex have the potential to improve forecasts of rapid deepening and eyewall replacement cycles by establishing the conditions under which such processes are favored.

RELATED PROJECTS

The diagnosis of the influence of asymmetric flow features on hurricane intensification in the Geophysical Fluid Dynamics Laboratory (GFDL) model was made in collaboration with Dr. R. Tuleya of GFDL (<http://www.gfdl.gov/hurricane.html>) . The utilization of the MM5 model was made in collaboration with the ONR-supported research project of Prof. R. Smith at the University of Munich (<http://www.meteo.physik.uni-muenchen.de>).

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